(54) Article comprising a micro-structured optical fiber, and method of making such fiber

(57) Disclosed are non-periodic microstructured optical fibers that guide radiation by index guiding. By appropriate choice of core region and cladding region, the effective refractive index difference Δ between core region and cladding can be made large, typically greater than 5% or even 10 or 20%. Such high Δ results in small mode field diameter of the fundamental guided mode (typically < 2.5 μm), and consequently in high radiation intensity in the core region. Exemplarily, a fiber according to the invention has a solid silica core region (51) that is surrounded by an inner cladding region and an outer cladding region. The cladding regions have capillary voids (52, 53) extending in the axial fiber direction, with the voids (53) in the outer cladding region having a larger diameter than those (52) in the inner cladding region, such that the effective refractive index of the outer cladding region is greater than that of the inner cladding region. Non-periodic microstructured fiber potentially has many uses, e.g., as dispersion compensating fiber (with or without dispersion slope compensation), as amplifying fiber, as laser, as saturable absorber, for fiber gratings, and for non-linear elements. A method of making microstructured fiber is also disclosed.

FIG. 1                                          10
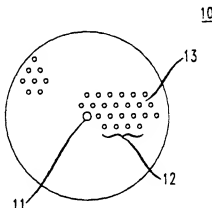
## Description

## Cross Reference to Related Application

This application claims priority of provisional application Serial No. 60/018,716, filed May 31, 1996.

## Field of the Invention

This invention pertains to "microstructured" optical fiber, to articles and systems (collectively "articles") that comprise such fiber, and to methods of making such fiber.

## Background of the Invention

Optical fiber communication systems typically comprise a variety of fibers and fiber-based components, e. g., low loss transmission fiber, Er-doped amplifier fiber, dispersion compensating fiber, and fiber with in-line refractive index gratings. All of these achieve guiding by means of total internal reflection, based on the presence of a solid core of relatively high refractive index that is surrounded by a solid cladding that has relatively low refractive index.

Recently a new type of optical fiber has been proposed. See T. A. Birks et al., Electronic Letters, Vol. 31 (22), p. 1941 (October 1995), and J. C. Knight et al., Proceedings of OFC, PD 3-1 (February, 1996). The new optical fiber, referred to as a "photonic crystal" or "photonic bandgap" (PBG) fiber, involves a dielectric structure with a refractive index that varies periodically in space (in the x-y plane; it is independent of the z-coordinate, i.e., the longitudinal coordinate of the structure), with a period of the order of an optical wavelength (e.g., about 1 - 2μm). According to the authors of the above cited references, in such a structure Bragg diffraction can take place, such that the structure exhibits a photonic stop band for certain values of wavelength and propagation direction. In consequence of the Bragg diffraction, radiation of certain wavelengths can only propagate in the longitudinal direction, with essentially no lateral leakage. The structure thus is a guiding structure that achieves guiding by a mechanism that differs fundamentally from the index guiding of conventional optical fibers. PBG fiber is an example of a "microstructured" fiber, as the term is used herein.

The above-cited Birks et al. reference states that applications of PBG fibers "... arise from the unique properties of the fibers", and discloses that a polished PBG fiber could provide a sensitive water pollution-or bio-sensor, or a novel gas sensor, and that other applications could follow from the polarization properties of the structure.

The Birks et al. reference also discloses that work is under way to make PBG fiber "... by a multiple stack-and-draw process." The Knight et al. reference discloses that PBG fiber is formed "... by creating a hexagonal silica/air preform (including a deliberate defect to guide light) on a macroscopic scale and then reducing its size by several orders of magnitude by pulling it into an optical fibre." "The unit cell of the photonic crystal is formed by drilling a hole down the centre of a silica rod and milling six flats on the outside, to give a hexagonal cross-section." A central "defect" is introduced by substituting a solid hexagonal rod for a rod with a longitudinal bore. Multiple drawings of the compound structure resulted in a PBG fiber of hexagonal cross section, with 34μm flat-to-flat diameter, and 2.1μm pitch between air holes.

The prior art process of making PBG fiber is difficult and costly, and it clearly would be desirable to have available a simpler, less costly method for making microstructured fiber. This application discloses such a method. Furthermore, this application discloses a novel fiber (to be referred to as "non-periodic microstructured" fiber) that can be made by the novel method, as well as optical fiber communication systems and other articles that comprise microstructured fiber.

## Glossary and Definitions

In this application we distinguish between "refractive index" and "effective refractive index". The refractive index of a feature that consists of a given material (not excluding a void) is the conventional refractive index of the material. On the other hand, the "effective refractive index" of a feature of a fiber (e.g., of the cladding region) is the value of refractive index of the feature that gives, in a simulation of the fiber, the same optical properties as the actual fiber. If the feature is substantially homogeneous (e.g., the core region), then the effective refractive index of the feature will be substantially the same as the refractive index of the feature. If, however, the feature is non-homogeneous (e.g, a cladding region that comprises voids disposed in a matrix), then the effective refractive index of the feature will differ from both the refractive index of the voids and the refractive index of the matrix material. Roughly speaking, the effective refractive index of a non-homogeneous material can be considered to be a weighted average of the refractive indices of the constituents of the material. It is known that the effective refractive index N of a 2-component material meets the following condition:

$$(n_1 n_2)\left(\sqrt{f_1 n_2^2 + f_2 n_1^2}\right)^{-1} \le N \le \sqrt{f_1 n_1^2 + f_2 n_2^2},$$

where $n_1$ and $n_2$ are the refractive indices of the two components, and $f_1$ and $f_2$ are the respective volume fractions. For a material consisting of 50% b.v. air and 50% b.v. silica, this gives $1.164 \le N \le 1.245$. Exact values of effective refractive indices can be obtained by numerical simulation of the guiding properties of microstructured optical fibers, exemplarily using vector solutions of Maxwell's equations. Such calculations are known to those skilled in the art. See, for instance, "Pho-

tonic Crystals", J. D. Joannopoulos et al., Princeton University Press, 1995. Our simulation of the above referred to 50/50 air/silica material, as described in Example 2, gave N ~ 1.20.

The term "effective diameter" of a fiber region herein has its conventional meaning. For instance, for a fiber having a given core effective refractive index $N_o$ and a given cladding effective index $N_c$, the effective core diameter at a given wavelength λ is that core diameter of a step index profile that yields the same V-number as the actual fiber.

Cladding features are "non-periodically" disposed in the first cladding material if at least one of the cladding features is not at a position of a periodic array, or differs in some property (e.g., diameter) from the other cladding features.

The "Δ" of a microstructured fiber is $(N_o - N_c)/N_o$, where $N_o$ and $N_c$ are defined above.

## Summary of the Invention

We have discovered that microstructured optical fibers do not have to have the fully periodic "cladding" microstructure disclosed in the prior art. Indeed, we have so far been unable to verify the existence of a photonic bandgap in microstructured optical fiber. However, we have found that microstructured fibers can serve as optical waveguides, and can have properties that are unattainable in conventional optical fibers, provided that the fiber meets some simple conditions. Among these properties is an effective refractive index difference between core and cladding that can be much larger than the refractive index difference obtainable by means of doping. Such microstructured fibers can be advantageously used in optical fiber communication systems, e. g., as dispersion compensating fiber, as photosensitive fibers and as rare earth-doped fibers.

The invention is embodied in an article (e.g., an optical fiber communication system) that comprises a microstructured optical fiber that comprises a (typically solid) core region surrounded by a cladding region that comprises a multiplicity of spaced apart cladding features that are elongate in the fiber axial direction and disposed in a first cladding material, the core region having an effective diameter $d_o$ and an effective refractive index $N_o$, the cladding features having a refractive index that differs from the refractive index of the first cladding material, and the cladding region having an effective refractive index that is less than $N_o$.

Significantly, the cladding features are non-periodically disposed in the first cladding material.

Microstructured fibers according to the invention can be single mode fibers or multimode (typically only a few modes) fibers. The core region typically will be solid material, either homogeneous or a combination of materials (e.g., an inner Si core region and an outer $SiO_2$ core region), but could comprise a liquid. For instance, the core region could comprise a glass capillary tube,

with the liquid drawn into the capillary after fiber drawing.

In exemplary currently preferred embodiments the core region is silica (doped or undoped), the first cladding material is silica, and the cladding features are voids. However, the core region need not have the same composition as the first cladding material, and/or the cladding features need not be voids. For instance, the core could comprise a silicon inner core (to impart to the core a higher effective refractive index), or the cladding features could be a polymer with predetermined refractive index, liquid crystal material or F-doped silica.

As those skilled in the art will recognize, elimination of the prior art requirement of strict periodicity of the cladding features can make it easier to manufacture microstructured fibers (and makes possible novel techniques for making such fibers). The elimination of the requirement is based on our realization that Bragg diffraction is not a requirement for radiation guiding in microstructured fiber, and that such fibers can be effective index guides.

By way of example, a currently preferred microstructured fiber according to the invention has an inner cladding region and an outer cladding region, with the cladding features in the inner cladding region being voids of larger diameter than the void cladding features of the outer cladding region. The inner cladding region thus has effective refractive index $N_{ci}$ less than the effective refractive index $N_{co}$ of the outer cladding region. A homogeneous silica outer cladding is typically provided for strength reasons. Such fiber can exhibit large dispersion (e.g., dispersion that is more negative than - 300 ps/nm-km) at a predetermined wavelength λ (e.g., 1.55 μm) and for a fundamental guided mode, and thus can be used advantageously for dispersion compensation. Furthermore, the fiber can have large dispersion slope, such that the fiber can provide dispersion compensation over a significant wavelength range, e.g., 20 nm or more. Such fiber also can have a small mode field diameter, e.g., less than 2.5 μm at λ and for the fundamental mode. Fiber according to the invention that comprises a photosensitive material in the core region can advantageously be used for optical fiber gratings, and fiber that comprises one or more rare earths (e.g., Er) in the core region can advantageously be used for fiber amplifiers and/or lasers. All of these applications benefit from the large Δ that can be attained in microstructured fibers according to the invention.

The invention is also embodied in a method of making microstructured optical fibers. The method comprises providing a core element (e.g., a silica rod) and a multiplicity of capillary tubes (e.g., silica tubes). The capillary tubes are arranged as a bundle, with the core element typically in the center of the bundle. The bundle is held together by one or more overclad tubes that are collapsed onto the bundle. The fiber is then drawn from the thus prepared preform.

Significantly, one end of the capillary tubes is

sealed, either before or after assembling the bundle, and the fiber is drawn from the other end of the bundle (preform). The resulting internal pressure in the capillary voids serves to maintain the capillary voids open. On the other hand, the voids between the capillary tubes remain open, and thus readily collapse during drawing.

The above described method can be practiced with periodic or non-periodic cladding features. In the latter case, the cladding features can vary in size or be arranged irregularly, provided only that the effective refractive index profile of the resulting fiber is such that the fiber supports the desired guided mode or modes.

## Brief Description of the Drawings

FIGS. 1 and 2 are schematic depictions of microstructured fibers in cross section;

FIG. 3 schematically shows an optical fiber communication system comprising a microstructured fiber;

FIG. 4 shows a further embodiment of a microstructured fiber in schematic cross section;

FIG. 5 shows a portion of the cross section of an exemplary non-periodic microstructured fiber; and

FIG. 6 shows the dispersion spectrum of a length of the fiber of FIG. 5.

## Detailed Description of Some Preferred Embodiments

As those skilled in the art will recognize, the microstructured fibers of interest herein have finite size (e.g., about 125 µm diameter) in the x-y plane, i.e., the plane normal to the longitudinal (z) coordinate of the fiber, and typically have substantially infinite extent (e.g., meters or even kilometers) in the longitudinal direction.

PBG fibers as proposed by Birks et al. have a central structural feature (referred to as the "defect"; it should be emphasized that this terminology is used to indicate the presence of an element that differs in some way from the elements in an otherwise uniform array. It does not imply a fault or unintended feature) that is surrounded by a periodic array of cladding features. Herein we will refer to the defect as the "core region". The core region need not be at the center of the fiber structure, although in practice it will generally be centrally disposed. The core region in PBG fiber breaks the symmetry of the structure. It can differ from the cladding features in any of a wide variety of ways, e.g., with regard to size, or with regard to refractive index. The latter can vary widely, from 1 (air) through 1.45 (silica) to larger values associated with different glasses or even non-glass materials such as semiconductors. Indeed, in principle the only limitation on the choice of core region is compatibility with the process of making the fiber.

The cladding features of PBG fiber similarly can consist of a void, or any suitable (second) material (first material) matrix. The features are disposed in a (first material) matrix. The features are disposed to form a periodic array, with one of the sites of the array occupied by the above-described core region. By way of example, the array is formed by a multiplicity of elongate voids of a given diameter that are arranged in a triangularly symmetric pattern, as shown schematically in Fig. 1, wherein numerals 10-13 refer, respectively, to an exemplary PBG fiber in cross section, the core region, the cladding feature array, and an exemplary "unit cell" of the array.

The array does not necessarily have a unit cell of triangular symmetry. Among other possible arrays are those with square unit cell and those with hexagonal unit cell, the latter being schematically shown in Fig. 2, wherein numeral 23 refers to an exemplary hexagonal unit cell.

We have discovered that the stringent requirements that were postulated by the above cited references can be considerably relaxed. In particular, we have discovered that there is no need for periodicity in the x-y plane (cross section). Instead, it is necessary that the fiber possesses a core region having an effective index of refraction that is significantly higher than the effective index of refraction of a cladding region that surrounds the core region and comprises a multiplicity of microstructural cladding features, e.g., capillary voids, with the cladding features not necessarily forming a periodic array. Indeed, the cladding features can even be randomly distributed and vary in size or other relevant property, provided that the fiber has a suitable effective refractive index profile. This of course constitutes a profound departure from the prior art PBG fibers.

FIG. 5 schematically shows a relevant portion of a non-periodic microstructured optical fiber. The structure comprises a solid core region 51 surrounded by an inner cladding region comprising first cladding features 52, arranged in basically hexagonal form, with the inner cladding region surrounded by an outer cladding region comprising second cladding features 53, not all of which are shown.

Exemplarily, the cladding features are voids, with the remainder of the structure being glass, e.g., silica. In a particular embodiment, the first and second cladding features have diameter 0.833 µm and 0.688 µm, respectively, with the center-to-center spacing of the cladding features being 0.925 µm. The first cladding features are positioned such that the inscribed circle of core region 51 is 1.017 µm.

As will be recognized by those skilled in the art, the core region, consisting of glass, will have an effective refractive index substantially equal to the refractive index of the glass. The inner cladding region has a larger ratio of void to glass than the outer cladding region. Consequently, the inner cladding region has a lower effective refractive index than the outer cladding region, and both cladding regions have lower effective refractive index than the core region.

FIG. 6 shows the computed dispersion spectrum 61 of the above described exemplary microstructured fiber, with the glass being silica, and the capillary features be-

sealed, either before or after assembling the bundle, and the fiber is drawn from the other end of the bundle (preform). The resulting internal pressure in the capillary voids serves to maintain the capillary voids open. On the other hand, the voids between the capillary tubes remain open, and thus readily collapse during drawing.

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lary glass remains rigid enough to be substantially un-deformed. Suitable metals include Al, Pb, Au, Ag and Cu, among others, as described by W. H. Grodkiewicz et. al. in Mat. Res. Bull., Vol. 10 (10), p. 1085 (1975). A suitable second glass should preferably have relatively low viscosity (is "molten") at the appropriate working temperature, whereas the capillary material is relatively rigid at that temperature. The second-to-first material ra-tio (analogous to the above referred to air-to-glass ratio) is inter alia a function of the wall thickness of the first material tube.

Exemplarily, non-periodic microstructured fibers can also be produced from porous material (typically po-rous glass, exemplarily silica gel), provided the glass/ air ratio of the material can be controlled. Known sol/gel processes of making porous silica bodies allow such control. Drawing fiber from a preform that comprises a porous glass cladding region can be expected to result in randomly distributed elongate voids.

The guiding properties of microstructured fibers de-pend, in general analogy to those of conventional index-guiding fiber, on fiber geometry and effective refractive index profile. As is the case for conventional fiber, com-puter simulations can be used to determine the specific structure that will provide a desired property or charac-teristic. Algorithms have been proposed and used to de-termine the optical properties of 2-dimensional and 3-di-mensional photonic crystals. See, for instance, J. D. Joannopoulos et al., "Photonic Crystals", Princeton Uni-versity Press, 1995, especially pp. 127-129; J. B. Pen-dry, J. Modern Optics, Vol. 41(2), p. 209 (1994); K. M. Leung, J. Optical Society of America. Vol. 10(2), p. 303 (1993).

Computer simulation generally involves solution of vector Maxwell's equations by finite element tech-niques, yielding the optical vector fields in a region of interest, and thus yielding complete information about optical propagation in the region. Thus, the fiber geom-etry, including array symmetry, index differences, sec-ond-to-first material ratio (or void/material ratio), and core properties can be designed to yield the desired properties of a microstructured fiber.

Conventional (index-guiding) optical fibers typically are designed to have at most of few percent refractive index difference Δ between core and cladding, primarily because, for Δ greater than about 2%, the loss of a sin-gle mode fiber increases significantly with increasing Δ. On the other hand, in microstructured fiber the index dif-ference can be much larger, typically at least 5%. Fur-thermore, microstructured fiber has parameters (e.g., symmetry, structure size, second-to first material vol-ume ratios, core properties) that do not have a counter-part in conventional index-guided fiber, and which pro-vide greater design freedom to the designer of micro-structured fiber, making possible novel devices based on such fibers.

For instance, in consequence of the large range of index difference potentially available in microstructured fiber, such fiber can be tailored to have relatively large (in absolute value) waveguide dispersion. Microstruc-ture fiber thus can advantageously be used as disper-sion compensator in an optical fiber communication sys-tem, including for dispersion slope compensation.

FIG. 3 schematically shows an exemplary optical fiber communication system 30 with numerals 31-37 re-ferring to a transmitter, signal radiation of wavelength λ (e.g., 1.3 or 1.55μm), optical transmission fiber, optical couplers, a length of microstructured fiber, optional fur-ther transmission fiber, and receiver, respectively. Other conventional components (e.g., optical amplifiers, pump lasers, optical isolators, Bragg gratings, WDMs etc.) will typically be present but are not shown.

Index guiding dispersion compensating (DC) fibers are known, as is their use in optical fiber communication systems to compensate for the dispersion of a given length of transmission fiber. For instance, DC fiber can be used to facilitate 1.55μm transmission over optical fiber that has minimum dispersion in the 1.3μm commu-nication wavelength range. The transmission fiber ex-emplarily has chromatic dispersion of about 17 ps/ nm·km and prior art DC fiber exemplarily has chromatic dispersion of about - 150 ps/nm·km. Thus it can readily be seen that a relatively long length (e.g., 13.6 km) of prior art DC fiber typically is required to compensate for the dispersion of a typical length (e.g., 120 km) of trans-mission fiber. On the other hand, microstructured fiber can be designed to have relatively large (positive or neg-ative, as desired) chromatic dispersion, such that a rel-atively short length (e.g., 1.3 km) of microstructured DC fiber can compensate the dispersion of the transmission fiber.

A significant aspect of the design of the microstruc-tured DC fiber is selection of the core, which can range from silica (refractive index about 1.45) to material (e. g., Si) having an index high compared to silica, yielding large effective index differences, exemplarily > 10% and more. Details of the design can be determined by com-puter simulation in known manner, typically by solution of the vector Maxwell's equations.

More broadly, microstructured fiber not only can be readily designed as high Δ fiber, but can for instance also be designed to have, in addition to the high Δ, a photosensitive core or a rare earth doped core.

A microstructured fiber with high Δ and photosensi-tive core is of considerable interest because such a fiber gives a small (e.g., 2. 5 μm or less) mode diameter of the guided radiation, resulting in high optical intensity in the core, with attendant increased non-linearity in the fiber. This in turn makes it possible to provide a fiber Bragg saturable absorber, a device that can be advan-tageously used in, for instance, a mode-locked fiber la-ser. The high nonlinearity of high Δ microstructured fiber with photosensitive core also facilitates all-optical non-linear Kerr switching in fiber, using a Bragg or long pe-riod grating. Such fiber exemplarily has a Ge, B or Sn-doped core, and typically is subjected to a known $H_2$

and/or $D_2$ treatment before grating "writing", to increase the photosensitivity of the core.

A microstructured fiber with big Δ and rare earth doped core can be readily produced, for instance, by using a rare earth-doped (e.g., Er) core rod in a structure as shown in FIG. 5. Such fiber offers considerable advantages over conventional rare earth-doped fibers. Among these is lower required power, due principally to the high attainable optical intensity in the core. Current rare earth-doped fibers typically have Δ's larger than those of conventional transmission fibers, to decrease laser and amplifier threshold powers and increase efficiency. Using a rare earth-doped high Δ microstructured fiber instead of a conventional rare earth-doped fiber can result in dramatically reduced threshold power, making devices such as remotely pumped amplifiers more practical and less expensive. Thus, a remotely pumped optical fiber communication system that comprises rare earth-doped high Δ (e.g., > 5%) non-periodic microstructured fiber is an exemplary and preferred article according to this invention. In such a system, the pump radiation source typically is more than 200 m (frequently many kilometers) from the fiber amplifier.

In some applications of optical fiber it is desirable to have available optical fiber having large non-linearity, as conventionally expressed by the values of the second and third order coefficients of the susceptibility, usually designated $\chi^{(2)}$ and $\chi^{(3)}$. Microstructured fiber can be readily designed to have large third-order nonlinearity. Since most of the guided optical power is in the core region, the amount and character of the fiber non-linearity is largely determined by the material and size of the core region. Exemplarily, if the core region has large non-linearity, then the fiber will exhibit large non-linearity and be useful for, e.g., parametric amplification. This can be accomplished by, e.g., providing a core region that consists of multicomponent glass having large non-linearity, e.g., Pb-doped silica.

However, as discussed above, high Δ microstructured fiber can exhibit large non-linearity even if the core region is undoped, or doped with a dopant that does not significantly increase the nonlinearity. This is due to the small mode field that is a consequence of the high Δ of the fiber.

The use of microstructured fiber in optical fiber communication systems is not limited to the above described exemplary uses, and undoubtedly other uses will be discovered as microstructured fibers become better known and understood.

Furthermore, microstructured fibers are not limited to fibers with an array of cladding features, of the type shown schematically in FIGS. 1, 2 or 5. FIG. 4 shows an alternative microstructured fiber 40 having circular symmetry, with the core feature 41 surrounded by a multilayer 421-42n (exemplarily more than 10 or even 20 layers) cladding, with alternating relatively high and low refractive indices. The refractive indices and layer thickness are selected such that the structure has a desired effective refractive index profile. For instance, the layer thicknesses can be chosen such that an inner cladding region has a relatively low effective refractive index, and an outer cladding region that surrounds the inner cladding region has an effective refractive index of value between that of the core region and the inner cladding region. Such a microstructured fiber can be made, for instance, by drawing from a preform, with the described multilayer cladding formed by, e.g., a conventional deposition technique such as MCVD, or by collapsing a multiplicity of glass tubes around the core feature. Optional outer cladding 43 can be conventional.

## Example 1

Microstructured fiber is made as follows. A multiplicity (exemplarily 169) of silica capillary tubes (outside diameter 0.718 mm, inside diameter 0.508 -mm, length 12 inches) is provided, and arranged in a close-packed bundle. The center tube of the bundle is replaced by a solid silica rod of outside diameter 0.718 mm. One end (to be referred to as the "first" end; the other end will be referred to as the "second" end) of each capillary tube in the bundle is sealed, without sealing the interstitial spaces in the close packed bundle. Silica tubes, of inner diameter slightly larger than the diameter of the bundle, are slid over the first and second ends of the bundle, respectively, and the combination is mounted in a conventional glass-working lathe. The end of one of the tubes is collapsed, with the aid of a vacuum, onto the first end of the bundle. This is followed by collapse of the end of the other tube onto the second end of the bundle, and pulling off this tube such that the bundle remains in the desired arrangement.

After making a hole in conventional fashion through the remaining silica tube near the first end of the bundle, a thin (exemplarily 1 mm wall thickness) silica overcladding tube is slid over the assembly past the hole, and is collapsed onto the bundle at the first end, and then at the second end, such that a vacuum can be drawn through the hole. Subsequently, the torch of the lathe is traversed from the second to the first end such that the overcladding tube is collapsed around the bundle. The overcladding step optionally is repeated with a silica tube selected to yield the desired array pitch and fiber diameter. Exemplarily, a standard (19 x 25 mm diameter) silica tube is used.

The thus produced preform is removed from the lathe and is mounted, secured and down, on a draw tower, and fiber is drawn from the preform in conventional fashion. The resulting fiber has 125μm outside diameter, 1:1 glass-to-air ratio, 2μm array pitch, with the cladding voids forming seven concentric layers around the central defect, with triangular unit cell. The fiber is coated in conventional fashion, and has optical properties substantially as predicted by a computer simulation.

Example 2

Non-periodic microstructured fiber is made substantially as described in Example 1, except that the core feature is a silica rod of diameter .718 mm, the rod is surrounded by six silica tubes of inner diameter .615 mm and outer diameter .718 mm, which in turn are surrounded by more than four layers of silica tubes of inner diameter.508 mm and outer diameter .718 mm, substantially as shown in FIG. 5. This preform is overlaid with silica tubes selected to yield, after drawing a desired fiber diameter. Specifically, preform diameter is 97 mm. This preform is drawn into fiber having 125 μm diameter, having a microstructured region as shown in FIG. 5, with 1.017 μm diameter core region (as represented by the diameter of the inscribed circle), center-to-center spacings 0.925 μm, and voids of 0.833 μm and 0.688 μm and 0.88 μm. The fiber has a dispersion spectrum substantially as shown in FIG. 6.

**Claims**

1.  An article comprising a microstructured optical fiber having an axial direction and a cross section perpendicular to said axial direction, the optical fiber comprising a core region (51) surrounded by a cladding region that comprises a multiplicity of spaced apart cladding features (e.g., 52) that are elongate in the axial direction and disposed in a first cladding material, the core region having an effective refractive index $N_o$, the cladding features having a refractive index that differs from a refractive index of the first cladding material, and the cladding region having an effective refractive index that is less than $N_o$;
    CHARACTERIZED IN THAT
    the cladding features are non-periodical cladding features.

2.  Article according to claim 1, wherein the core region and the first cladding material are silica, and the cladding features are voids.

3.  Article according to claim 1, wherein the core region comprises a rare earth element.

4.  Article according to claim 1, wherein the core region comprises a photosensitive material.

5.  Article according to claim 1, wherein the core region comprises a material selected to provide the fiber with increased third order non-linearity.

6.  Article according to claim 1, wherein $N_o$ and the refractive index of the cladding region are selected such that the microstructured optical fiber exhibits, at a predetermined wavelength λ and for a fundamental guided mode, a dispersion that is more negative than - 300 ps/nm·km.

7.  Article according to claim 1, wherein the cladding region comprises an inner and an outer cladding region having effective refractive index $N_{ci}$ and $N_{co}$, respectively, with $N_{ci} < N_{co}$.

8.  Article according to claim 1, wherein the cladding features are substantially randomly distributed in said cross section of the microstructured optical fiber.

9.  Article according to claim 1, further comprising an optical signal transmitter, an optical signal receiver, and an optical fiber transmission path that signal transmissively connects said receiver and transmitter, wherein the transmission path comprises a first length of said microstructured optical fiber.

10. Method of making a microstructured optical fiber, the method comprising

    a) providing a core element and a multiplicity of capillary tubes, said capillary tubes and the core element arranged as a bundle, with the core element surrounded by the capillary tubes
    b) forming a preform by a process that comprises collapsing a cladding tube around the bundle, and
    c) drawing optical fiber from a heated end of the preform;

    CHARACTERIZED IN THAT the method further comprises, prior to step c), sealing a first end of the capillary tubes, the capillary tubes in the preform being disposed such that the sealed off first ends are remote from the heated end of the preform.
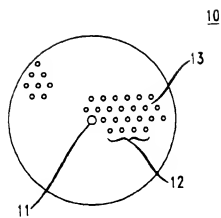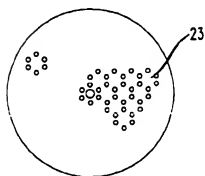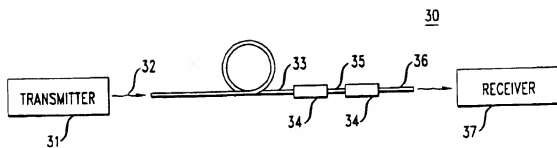
FIG. 1
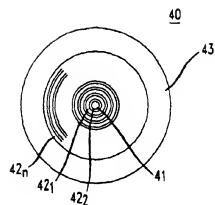


FIG. 2
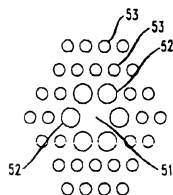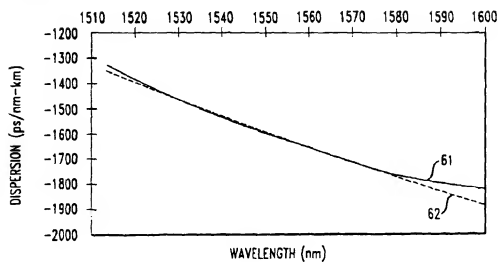


FIG. 3

FIG. 4



FIG. 5



FIG. 6

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EP 97 30 3414

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| Category | Citation of document with indication, where appropriate, of relevant passages | Relevant to claim | CLASSIFICATION OF THE APPLICATION (Int.Cl.6) |
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The present search report has been drawn up for all claims

| Place of search | Date of completion of the search | Examiner |
|---|---|---|
| MUNICH | 29 August 1997 | Beaven, G |

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The present search report has been drawn up for all claims

| Place of search | Date of completion of the search | Examiner |
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